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CHARACTERISTICS OF A 2.17-MEGAWATT FAST-SPECTRUM REACTOR CONCEPT USING AN AXIALLY MOVING REFLECTOR CONTROL SYSTEM

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16. Abstract

Neutronic, fluid flow, and heat-transfer calculations were performed for a reactor concept which makes extensive use of refractory metals for structure, cladding the uranium nitride fuel, and reflectors. Lithium-7 is the coolant. A design objective of operation for 50 000 hours at 2.17 MW is achieved by fuel zoning to shape the power and the temperature distributions in the core and equalize fuel cladding stresses. Calculations show that reactivity control requirements can be met with an axially moving reflector outside of the pressure vessel.

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SUMMARY

Neutronic, fluid flow, and heat-transfer calculations were performed for a reactor concept designed to produce 2.17 thermal megawatts for 50 000 hours with a lithium-7 coolant outlet temperature of 1222 K (2200° R). The inlet temperature is 1167 K (2100° R). The 253 fuel pins are clad with the tantalum alloy T-111. The fuel is uranium nitride with the uranium enriched to 93.2 percent uranium-235. The fuel is arranged in three radial zones varying from 33.4 to 42.0 volume percent of the core in order to equalize fuel cladding stresses during core life.

Reactivity control is achieved by axial translation of molybdenum radial reflectors located outside of the T-111 pressure vessel. Estimated reactivity control requirements total 9.2 percent $\Delta k/k$. The required multiplication factor for the cold, clean, unzoned reactor is 1.055. The corresponding calculated values for the zoned reactor are 9.4 percent $\Delta k/k$ and 1.0925, respectively. If reactor design to preclude a water immersion accident is included, control swing would be reduced to 7.9 percent $\Delta k/k$, which would necessitate a reduction of the contingency allowance in the required control swing to 0.7 percent $\Delta k/k$. In-core reactivity worths of fuel cladding materials and reactor coolant were determined along with flux spectra and power distribution. The average core flux is 1.03×10^{14} neutrons per square centimeter per second with a median fission energy of 0.36 MeV. Maximum peak-to-average power factors of 1.57 (reflector withdrawn) and 1.36 (reflectors inserted) were calculated.

Fluid flow and heat-transfer calculations indicate that there is less than a 1-percent variation in the radial flow distribution, that the core pressure drop is 0.51 newton per square centimeter (0.74 psi), and that 12 percent of the coolant flows through the passive and peripheral channels. Peak fuel temperature in the core is 1289 K (2320° R). Complete blockage of one flow channel causes a 44.5 K (80° R) increase in the adjacent fuel temperature.

Passive cooling of the movable radial reflectors was acceptable. A surface coating (on the molybdenum) with an emissivity of 0.3 is required to lower the maximum temperature to the pressure vessel temperature.

INTRODUCTION

The purpose of this report is to describe some of the design characteristics of a nuclear reactor concept for the generation of electric power in space. The reactor power level is 2.17 thermal megawatts which could provide about 500 electrical kilowatts if used with Brayton cycle power conversion equipment.

The reactor is characterized by the extensive use of high-temperature, high-strength refractory metals as structural materials, fuel-element cladding, and reflectors. The design requires the use of refractory materials in order to obtain the material strength properties required to achieve long lifetime (50 000 hr) at high temperature.

Previous reports have considered three types of reactivity control systems for compact fast-spectrum reactors. Reference 1 discusses rotating fuel drums located around the periphery of the core. Reference 2 compares rotating fuel drum control with poison drum control for similar core configurations. Both types of control were adequate for the configurations in reference 2. However, a subsequent report (ref. 3) on poison drum control for a reactor very similar to the reactor in the present study shows poison drum control to be marginal. The third type of control uses axially translating radial reflectors. Reference 4 discusses the effects of reflector materials, dimensions and other design perturbations on control reactivity for a similar reactor configuration. A fourth method (poisoned control rods) was considered briefly, but disadvantages of increased core size, high-temperature chemical reactions with good neutron absorbing material such as B_4C, and control rod cooling problems were found with no compensating advantages.

For this report we have chosen to use the sliding reflector method primarily because the entire control system can be located in the more hospitable radiation and temperature environment outside of the pressure vessel.

In the following sections we describe the reactor concept and discuss, in some detail, the neutronics design and the thermal and fluid flow design.

DESCRIPTION OF THE REACTOR

The core is a cylindrical pressure vessel containing 253 fuel pins positioned in a triangular-pitch lattice of 2.159-centimeters and bounded by top and bottom grid plates (figs. 1 and 2). A tubular honeycomb structure with the same pitch is used to define uniform lithium-7 coolant flow passages around each fuel pin. The fuel-pin outside diameter is 1.905 centimeters. The cladding on the fuel pin consists of 0.013-centimeter of tungsten and 0.147 centimeter of T-111. The tungsten is located between the uranium nitride fuel and the T-111. Enrichment in the uranium-235 isotope to 93.2 percent is

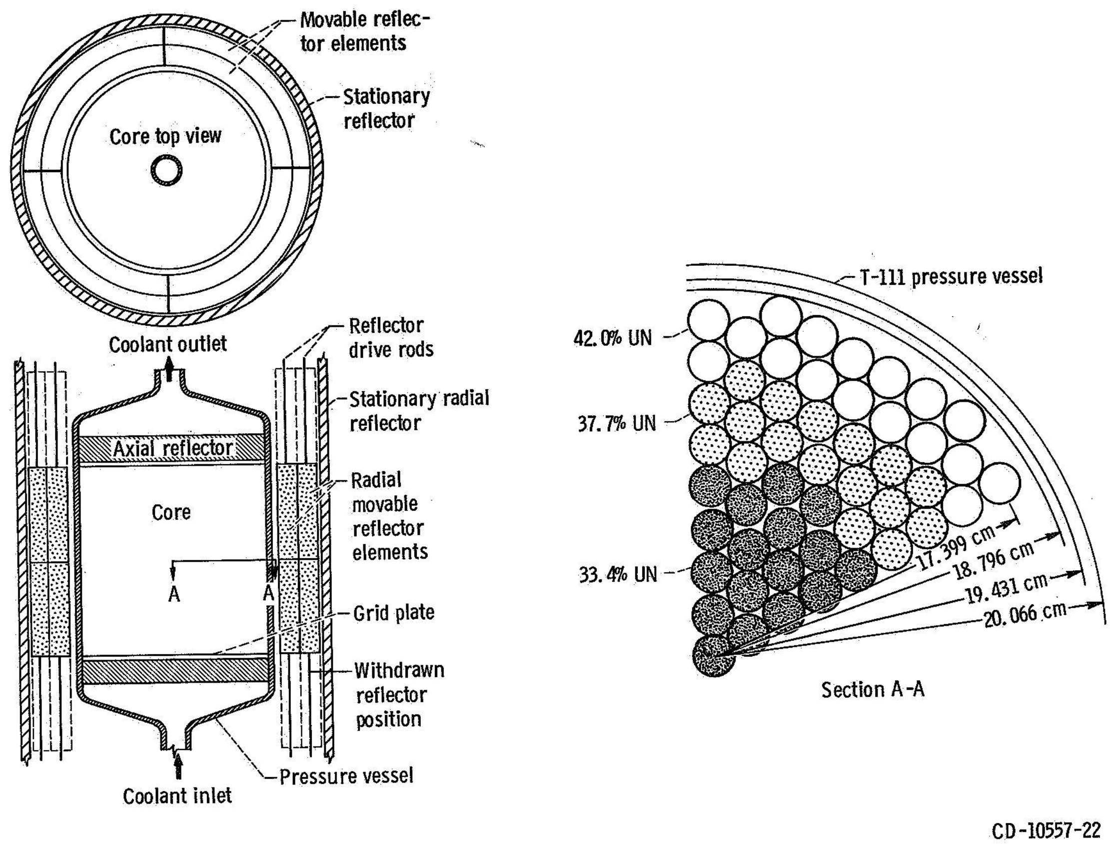

Figure 1. - Reactor schematic.

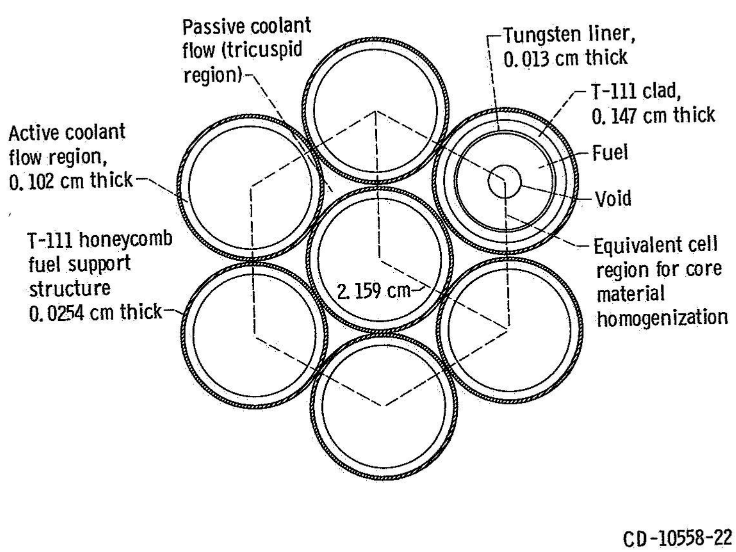

Figure 2. - Reactor core lattice and fuel pin detail.

assumed. The active core length is 37.592 centimeters. The 0.635-centimeter-thick T-111 pressure vessel has an inside diameter of 38.862 centimeters.

In order to equalize fuel cladding stress radially across the core and to enhance reflector worth, the fuel loading was varied in three radial zones. The inner zone (73 pins) contains 33.4 volume percent fuel in its cell structure, the intermediate zone (90 pins) has 37.7 volume percent fuel and the peripheral zone (90 pins) has 42.0 volume percent fuel. The average core fuel loading is 38.0 volume percent. Figure 1 shows a 60° sector of the core and the radial fuel zones. The circular regions shown in figure 1 are the T-111 honeycomb; the fuel pins fit inside the honeycomb. The loading variation is accomplished by varying the diameter of the central void space in each fuel pin (fig. 2). The void space provides room for fuel swelling and release of fission product gases.

Reactivity control is obtained by axial translation of movable radial molybdenum reflectors, one 4.0 centimeters thick and the other 4.5 centimeters thick. Thicknesses were selected to provide approximately equal reactivity worths in each reflector. These reflectors move along guide rods within an annulus formed by the pressure vessel and a 2.5-centimeter-thick stationary reflector. This stationary reflector provides a heat sink and a support structure for the movable reflectors. A 0.152-centimeter clearance is provided on each side and between the movable reflectors. The 10-centimeter-thick stationary axial reflectors are also made of molybdenum. All stationary reflectors are convectively cooled and 15 volume percent of each is allowed for the lithium-7 coolant. A 2.54-centimeter thick plenum region composed of the grid plates, fuel pin anchors, and lithium-7 separates the axial reflectors from the active core.

Although a shield design study was not made, its effect was estimated by assuming that a 7.62-centimeter-thick layer of shield material was wrapped around the stationary radial reflector. The material used is 70 volume percent lithium-6 hydride, 10 volume percent lithium-7, and 15 volume percent molybdenum.

NEUTRONICS DESIGN

Calculational Procedure

Neutron cross sections for use in criticality calculations were generated with GAM-II (ref. 5) using 13- and 4-group energy splits. The details and the adequacy of these energy groupings were described in previous reports (refs. 1 and 2). All cross sections were flux weighted over the spectrum that would be present in the region of their use; for example, core cross sections over a core spectrum, etc. Criticality calculations were performed with the neutron transport code TDSN (ref. 6). Although many calculations were made using a 1D S_4P_0 13-group set of options, 2D S_4P_0 four-group calculations were made when more accuracy was required. The notation scheme for code options can be described as follows; 1D is a one-dimensional approximation of the real geometry, S_4 represents the angular quadrature scheme of order 4 for solving the S_n transport equations, P_0 represents cross sections which contain a correction to approximate nonisotropic scattering based on a calculational scheme using only the first term of a Legendre polynominal expansion solution to the transport equation, and 13 group is the number of discrete energy groups for which the multigroup transport equation will be solved.

All reactivity effects were determined by the formula

$$\% \frac{\Delta k}{k} = \frac{k_1 - k_2}{k_1 k_2} \times 100$$

where

k_1 multiplication constant of reference reactor
k_2 multiplication constant of perturbed reactor

The model used for calculations (fig. 3) is a cylindricized version of the real geometry. Thus, the nearly hexagonal shape formed by the fuel cells in each core region was converted to a circular cross section, the dimensions being determined by conserving total atoms and volumes in each zone (fig. 1). Also, the 0.152-centimeter (60-mil) gaps (which exist at each movable reflector boundary in the real geometry) and the reflector guide and drive rods have been homogenized into the two movable reflector regions in figure 3. Material compositions of the various regions are listed in table I. The reflector guide and drive rods account for the 3 percent molybdenum in the reflector region after the movable reflectors are withdrawn.

In the development of circular dimensions for the core fuel zones, the variation from the actual core boundary became apparent (fig. 1). Although no attempt was made to calculate this boundary effect using a two-dimensional x-y calculation, consideration was given to creating a fourth fuel zone which would contain part of the outer row of fuel cells plus lithium-7. Dimensional limits for this zone are indicated in section A-A of figure 1 (17.399 and 18.796 cm, respectively). Calculational results indicated no significant change in the multiplication constant k but the power shape was distorted downward near the core edge. Consequently, there appeared to be no advantage to this scheme.

To determine the axial leakage required in a one-dimensional radial approximation to the cylindrical reactor geometry, a leakage synthesis study was performed. Thus,

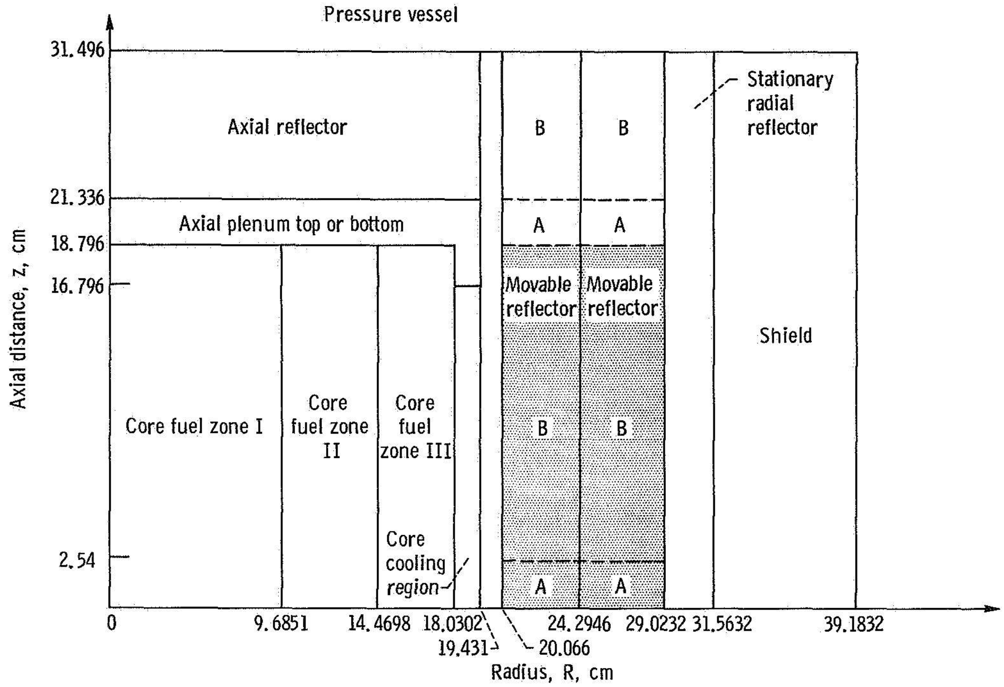

Figure 3. - Reactor calculational model. Shaded area represents vacated region when movable reflectors are withdrawn.

TABLE I. - MATERIALS FOR THE REACTOR MODEL

Material	Density, g/cm^3	Volume percent in -												
		Core zone			Core cooling region	Axial plenum		Axial reflector	Pressure vessel	Movable reflector			Stationary radial reflector	Shield
		I	II	III		Top	Bottom			[a]Inserted		Withdrawn (A or B)		
										A	B			
Uranium-235 nitride	14.2	33.4	37.7	42.0	---	--	--	--	---	--	--	--	--	--
Lithium-7	.516	25.2	25.2	25.2	100	57	72	15	---	--	--	--	15	10
Molybdenum	10.2	----	----	----	---	--	--	85	---	90	92	3	85	15
[b]T-111	16.72	24.4	24.4	24.4	---	28	19	--	100	--	--	--	--	--
Tungsten	19.3	1.5	1.5	1.5	---	--	--	--	---	--	--	--	--	--
[c]Lithium-6 hydride	.8	----	----	----	---	--	--	--	---	--	--	--	--	70
Void	------	15.5	11.2	6.9	---	15	9	--	---	10	8	97	--	5

[a]Two zones existed because of different amounts of structural materials

[b]The weight percentages of the constituents of T-111 used in the calculations are: 2.3 Hf, 8.5 W, and 89.2 Ta.

[c]The stoichiometric atom ratio of hydrogen to lithium-6 was reduced to 0.95.

alternate radial and axial calculations were made starting with a guess for transverse leakage and then using the computed leakage in each succeeding calculation until both the axial and the radial calculation produced the same k. This k then should be equivalent to a two-dimensional calculation. The extrapolated axial dimension (reflector savings plus core height) required to produce this axial leakage via the geometric buckling formula was calculated to be 51.1 centimeters.

Temperature effects were determined by increasing the radial and axial dimensions of the reactor components and reducing material densities by the appropriate thermal expansion coefficients. The difference between the k of this configuration and the reference reactor was then calculated.

Control System

Reactivity and reactivity control requirements. - The total reactivity worth needed in a control system to operate a reactor can be separated into a number of components. Each component considered in this study is discussed briefly below.

Temperature defect: The loss of reactivity resulting from core expansion and coolant density decrease when a cold critical reactor is brought to operating temperature is called the temperature defect. The Doppler effect would normally be included, but, since it has not been directly calculated for this reactor, it is discussed separately. The reference temperature for the cold reactor is taken to be 460 K (828° R), the melting point of the coolant. Temperatures of the various components in the core when operating at full power are itemized in table II along with the necessary thermal expansion coefficients. A reactivity loss of 0.90 percent $\Delta k/k$ was calculated between the cold reactor and the reactor at operating temperature. This reactivity is composed of 0.18 percent $\Delta k/k$ for the coolant expansion, 0.43 percent $\Delta k/k$ for radial expansion of the reactor, and 0.29 percent $\Delta k/k$ for axial expansion of the reactor. For the axial expansion calculation it was assumed that the uranium nitride fuel could expand freely in the axial direction. Axial expansion could be inhibited somewhat if the fuel were initially in intimate contact with the clad. The free expansion value is used, however, in setting reactivity control requirements.

Doppler effect: The Doppler coefficient for the reactor as a function of temperature is shown in figure 4. The shape of this curve is based on the empirical correlation equations in reference 7 and on the core compositions in table I. However, the magnitude of the coefficient has been reduced by a factor of 4 from that obtained using the equations in reference 7 to account for the harder spectrum in this core. Integration of the Doppler coefficient curve in figure 4 between the cold critical temperature (460 K or 828° R) and the core average operating temperature (1222 K or 2200° R) yields a reactivity decrease of 0.25 percent $\Delta k/k$.

TABLE II. - DATA FOR CALCULATING THERMAL

EXPANSION OF REACTOR

(a) Reactor temperatures			(b) Material properties	
Component	[a]Temperature		Material	[b]Linear thermal expansion coefficient, K^{-1}
	K	^{o}R		
Fuel	1233	2220	Uranium nitride	1×10^{-5}
Coolant	1195	2150	T-111	6.3×10^{-6}
Core structure	↓	↓	Molybdenum	5.5×10^{-6}
Pressure vessel	↓	↓	Lithium	(c)
Inner section of movable reflector	↓	↓		
Outer section of movable reflector	1089	1960		
Stationary reflector	833	1500		

[a]Estimated average temperature at design power.

[b]Estimated average over the temperature range of interest.

[c]Density (in g/cm^3) as a function of temperature determined from $p = 0.562 - 0.0001\ T$, where T is in degrees K.

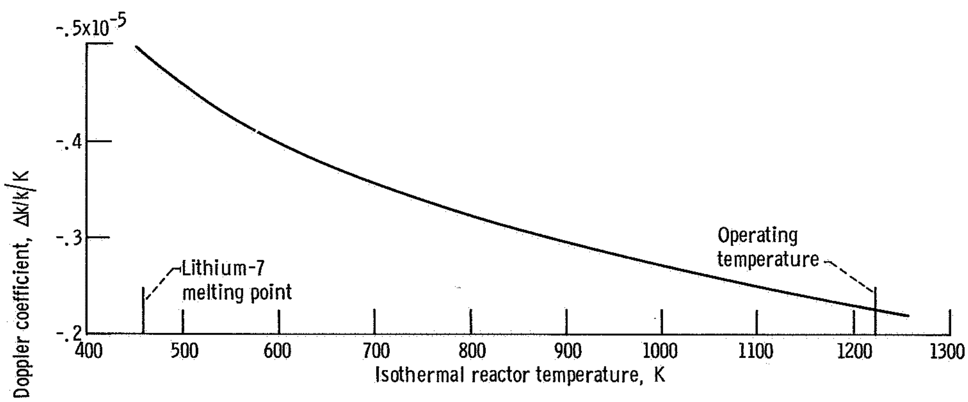

Figure 4. - Doppler coefficients of reactivity. (Doppler temperature defect, 0.25 percent Δk/k (460 to 1222 K).

Fuel burnup: The total energy required to produce 2.17 megawatts for 50 000 hours is 3.906×10^{14} watt-seconds. Based on an effective energy release of 187 MeV per fission, this would require 13.05×10^{24} fissions. There are 4.71×10^{26} atoms of uranium-235 in the core, giving an average burnup of 3.30 percent. Only uranium-235 atoms were considered because less than 1 percent of the fissions occur in uranium-238. The effect on reactivity is determined using the relation

$$\frac{\Delta k}{k} = 0.6 \times \frac{\Delta \text{ Fuel mass}}{\text{Fuel mass}}$$

which was obtained from criticality calculations in which the fuel loading was varied. Thus, $\Delta k/k = 1.98$ percent.

Fission products were calculated to have only a negligible effect on reactivity both directly (by absorption and scattering of neutrons) and via fuel cladding creep (1 percent design tolerance). Creep of the fuel cladding, resulting from the pressure of fission product gases and fuel swelling, restricts the coolant flow path, but this has little effect on temperature distributions or reactivity.

Fuel swelling: Long-term fuel swelling in the axial direction represents a significant reactivity effect. The radial growth is constrained to a large extent by the high-strength clad. Moreover, some growth into the central void can be expected. Axially, however, contact with the clad is the only restraint to axial growth. If it is assumed that, at operating temperature, intimate contact with the clad occurs, then the axial growth for the average fuel pin is estimated at 0.34 centimeter. The resulting loss in reactivity is 0.35 percent $\Delta k/k$ based on a calculated coefficient of 1.02 percent $\Delta k/k$ per centimeter of axial growth. A contingency allowance is included in the tabulation of reactivity and reactivity control requirements to account for uncertainties such as those just discussed.

Shutdown margin: A shutdown margin of 2 percent $\Delta k/k$ is assumed for this reactor.

Lifetime margin: In addition to the design lifetime of 50 000 hours, another criterion that must be met is operation for 20 000 hours even if one reflector control element sticks open at the beginning of life. A reflector control element represents both the upper and lower quarter sections of one of the movable reflectors. Thus, each movable reflector is comprised of four elements that can be operated either independently or as a unit. Reactivity worths for the various combinations of inner and outer movable reflector positions (assuming only unit operation of the control elements) are listed in table III. Since the proposed operating procedure is to approach criticality by completely closing one of the movable reflectors and then operating the other, only cases 1 and 2 in table III pretain to this analysis. For the most reactive condition of these two (case 2), the worth

TABLE III. - REACTIVITY WORTHS FOR

OPERATING REFLECTOR POSITIONS

Case	Reflector configuration	Reactivity worth[a], % $\Delta k/k$
1	Inside reflector closed; operate outer reflector	2.5
2	Outside reflector closed; operate inner reflector	3.85
3	Inside reflector open; operate outer reflector	5.55
4	Outisde reflector open; operate inner reflector	6.9
5	Operate both sections for movable reflector	9.4

[a]Worth calculated for unit operation of the four control elements of each movable reflector from open to closed position.

of one stuck element is 0.96 percent $\Delta k/k$. Should this element stick open, the amount of reactivity available in the control system for fuel burnup is 1.98 - 0.96 = 1.02 percent $\Delta k/k$. The reactivity needed for 20 000 hours full power operation is (20 000/50 000) × 1.98 = 0.79 percent $\Delta k/k$. Therefore, no additional reactivity is required.

Shutdown safety margin: As a safety criterion the reactor should be capable of shutdown at anytime during its operating lifetime with one control element stuck closed. Since this shutdown criterion is most severe for the most reactive condition, case 4 in table III will be considered. Shutdown is assumed attainable at a $k = 0.98$, and a margin of 2 percent $\Delta k/k$ is already included in the control system for the configuration with both reflectors withdrawn. For a reflector divided into four parts, one stuck element is worth

$$\left(\frac{6.9}{4}\right)\% \; \Delta k/k = 1.73\% \; \Delta k/k$$

Therefore, an additional shutdown margin of 1.73 percent $\Delta k/k$ must be added to the 2 percent previously included with a resulting shutdown k of 0.964.

Total control requirements: The reactivity control requirements are summarized in table IV. In the absence of experimental verification of the calculated values, an additional allowance is advisable. Thus 2 percent $\Delta k/k$ is included. The total requirement is then 9.2 percent $\Delta k/k$. Based on a shutdown multiplication factor of 0.964,

TABLE IV. - CONTROL

SYSTEM REACTIVITY

REQUIREMENTS

Component	Reactivity change, % $\Delta k/k$
Temperature defect	-0.90
Fuel destroyed	-1.98
Fuel swelling	-.35
Shutdown	-2.0
Doppler effect	-.25
Lifetime criterion	0
Safety criterion	-1.73
Contingency	-2.0
	-9.2

the resulting multiplication factor for the fully reflected, cold, beginning of life reactor should be 1.055.

Reflector worth. - The total worth of the movable reflectors was determined with both 1D S_4P_0 13-group calculations and with 2D S_4P_0 4-group calculations (table V). The 9.4 percent $\Delta k/k$ value from the two-dimensional calculations is considered the more accurate because a previous work (ref. 4) indicated that these calculations are more sensitive to geometric than to spectral approximations. The one-dimensional results are higher by 1 percent $\Delta k/k$.

The multiplication factors are higher than required (table V) but fuel removal can be

TABLE V. - TOTAL REFLECTOR WORTH

Calculation method	Multiplication constant		Movable reflector worth, % k/k
	Movable reflector withdrawn	Movable reflector inserted	
1D S_4P_0 13 group	0.9772	1.0873	10.4
2D S_4P_0 4 group	.9905	1.0925	9.4

used to adjust the multiplication factor. (Fuel removal would also alleviate a potential problem of exceeding a creep limit for the clad as discussed later in the section on core temperature and flow distribution.)

Reactivity worths for various positions of the movable reflectors are listed in table III.

Water Immersion Accident

The principal nonoperating accident that must be considered for this type of reactor is the possibility of water immersion during land transport or launch malfunction. Although the stationary reflector provides sealed containment, the integrity of this structure cannot be guaranteed in the event of an accident. Therefore, since the reactor will be in its shutdown configuration (all movable reflectors withdrawn), the presence of water in the space vacated by the reflectors must be considered.

Such a condition would decrease neutron leakage from the core and tend to increase k, possibly causing an excursion. To counteract this, a boron-10 sheath is placed around the pressure vessel to absorb reflected neutrons before they can reenter the core. The sheath will be removed when reactor operation is desired. To provide space for the sheath within the existing reactor design, the movable reflector thickness will be reduced by the required thickness of the safety sheath.

Calculations for a similar reactor configuration show that about a 2-centimeter thickness of boron-10 (used as a safety sheath) placed adjacent to the pressure vessel would be required to prevent a nuclear excursion in a water immersion accident. The resulting penalty for this reduction in movable reflector thickness is a reduction in reflector control swing to 7.9 percent $\Delta k/k$. Thus, this reactor configuration would still have sufficient control swing but design conservatism would be reduced because the contingency allowance would be reduced to 0.7 percent $\Delta k/k$.

Reactivity Worth of Reactor Materials

The reactivity worths of several possible material substitutions in the reactor design were calculated and are listed in table VI. These data represent the results of 1D S_4P_0 13-group calculations of reflected reactor configurations.

The results can be interpreted as follows:

(1) The lower neutron absorption cross section in the core resulting from the replacement of the T-111 fuel cladding with molybdenum causes core reactivity to increase 6.0 percent $\Delta k/k$. Similarly, the use of tungsten - 30 percent molybdenum - 25 percent rhenium (W - 30Mo - 25Re) increases core reactivity by 2.7 percent $\Delta k/k$.

TABLE VI. - REACTIVITY FOR SEVERAL POSSIBLE MATERIAL

SUBSTITUTIONS OR ADDITIONS

Materials	Reactivity worth, % $\Delta k/k$	Comments
Molybdenum for T-111 as fuel cladding	6.0	--
W-30Mo-25Re for T-111 as cladding	2.7	--
Natural lithium for lithium-7 as coolant	-1.9	Natural lithium contains 7.4 percent lithium-6
Loss of lithium-7 coolant	-.5	--
Increase T-111 in top plenum from 28 to 75.2 percent	-.08	Top plenum void held constant at 15 percent; bottom plenum was 19 percent T-111 and 72 percent lithium-7
Inclusion of a 2.54-cm lithium region in middle of top and bottom reflectors	-.05	Total molybdenum thickness held constant with and without lithium region

(2) The greater neutron absorption cross section of the coolant caused by replacing lithium-7 with natural lithium causes core reactivity to decrease 1.9 percent $\Delta k/k$.

(3) A loss-of-coolant accident results in a decrease of 0.5 percent $\Delta k/k$.

(4) Reactivity is relatively insensitive to material composition changes in the axial plenum and the axial reflector.

Core Characteristics

Certain data become available as a byproduct of the criticality calculations for the control system. These data are discussed in this section.

Power distributions. - Radial and axial power distributions were calculated (2D S_4P_0 4 group) along the core centerlines and edges. The data are presented as the ratio of local power density to the average power density in the core $P/\bar{P}$. Power distributions for the fully reflected reactor (movable reflectors inserted) are shown in figure 5 in which $P/\bar{P}$ ranges from a maximum of 1.36 at the core center to a minimum of 0.54 in the corner of the core. For a reactor with the movable reflectors withdrawn the comparable values for $P/\bar{P}$ were 1.57 and 0.48 (fig. 6).

Flux spectra. - Flux spectra at various locations in the reactor are plotted in figure 7. Progressive "hardening of the spectrum" (increasing the median neutron energy) occurs from the outside of the movable reflector to the core center. Some accumulation of neutrons below 5 keV occurs in the molybdenum reflector, but from the inside edge

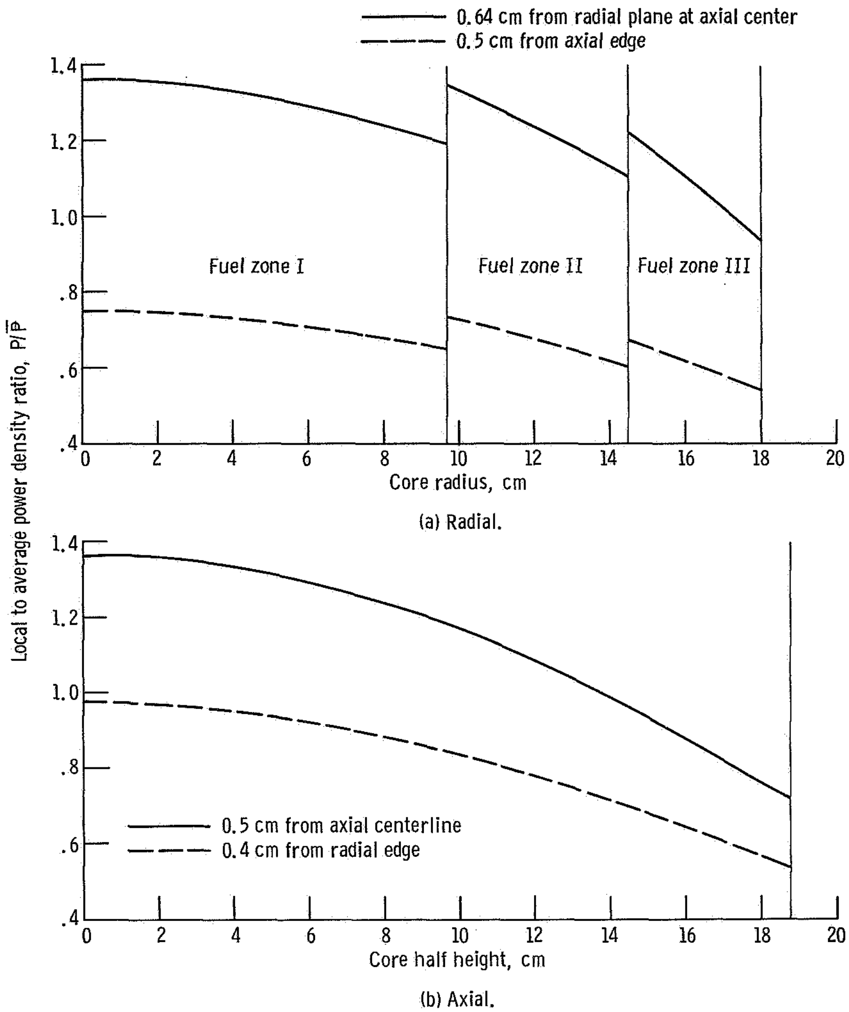

Figure 5. - Power distribution with reflectors closed.

of the reflector to the core center these neutrons are essentially nonexistent.

A double peak appeared in all curves, one around 0.4 to 0.7 MeV and another at about 0.1 to 0.2 MeV. At the core center the high energy peak dominated, but as the spectrum softened the low energy peak became the greater of the two. The source of these peaks was not investigated although it was noted that the minimum energy between the peaks coincided with a scattering resonance in the lithium-7 cross section.

Flux level. - The average flux in the core was calculated to be 1.03×10^{14} neutrons per square centimeter per second. The radial peaking factor (ratio of the flux at the center to the average flux) was 1.3 and the axial peaking factor was 1.2. Thus, the peak flux at the core center was 1.6×10^{14} neutrons per square centimeter per second. The median energy of the neutron flux in the core was 0.48 MeV.

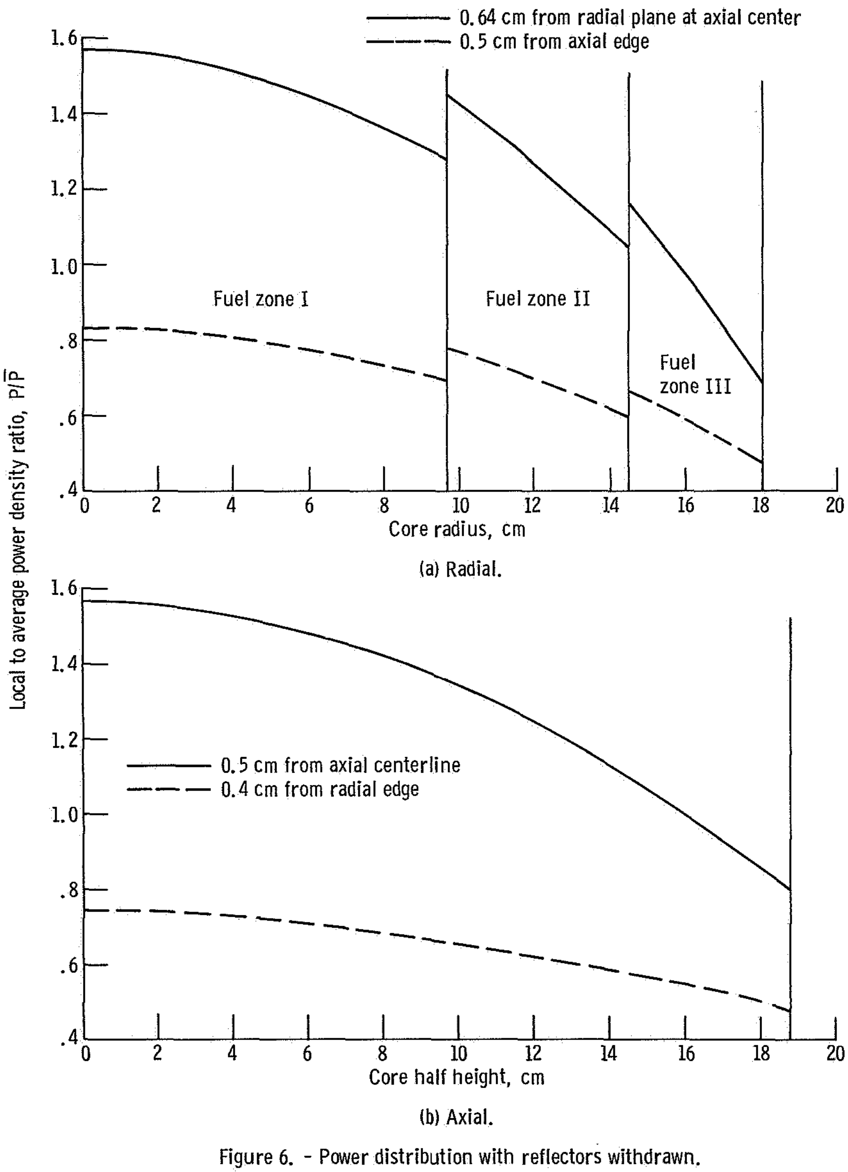

Figure 6. - Power distribution with reflectors withdrawn.

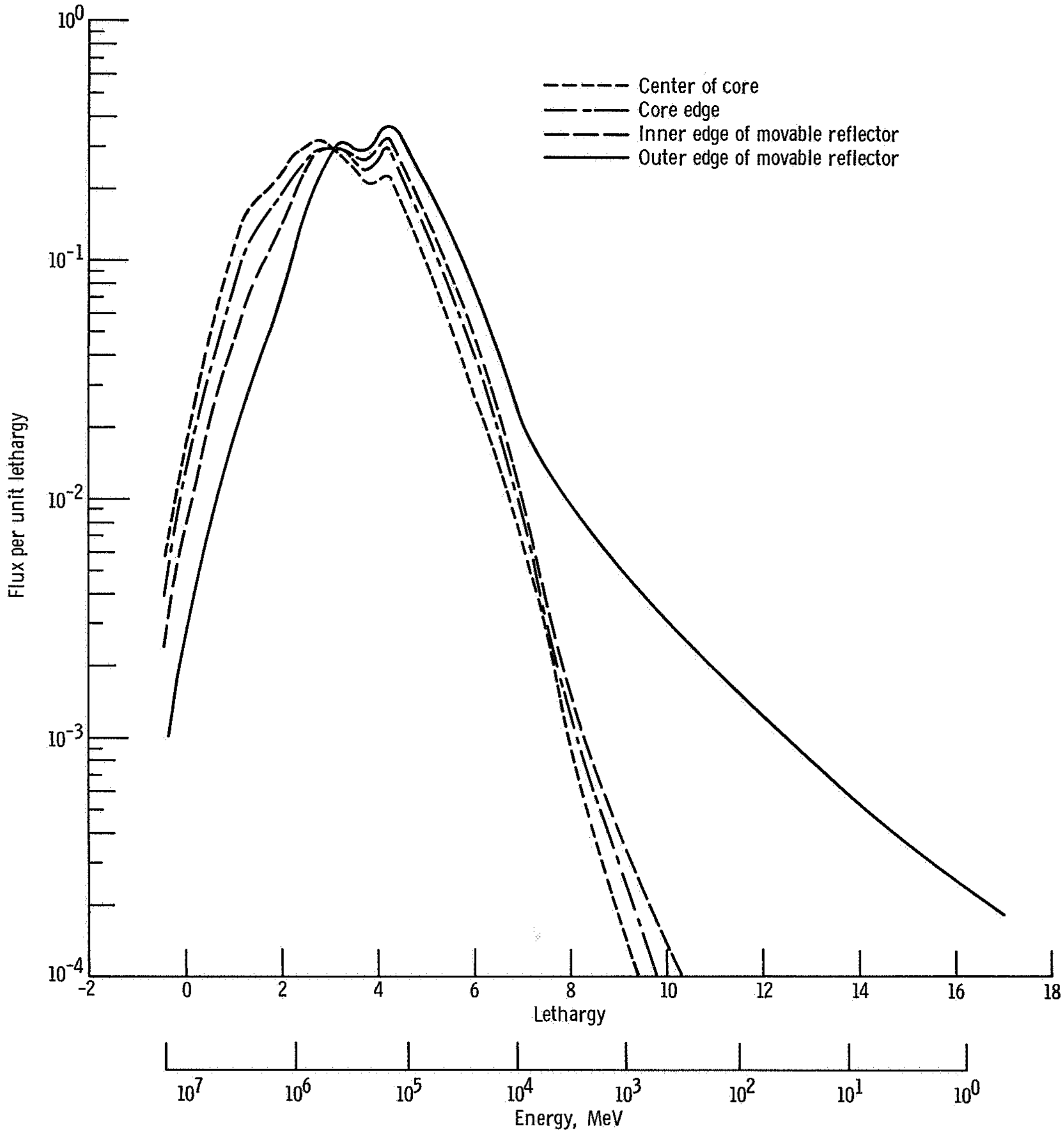

Figure 7. - Flux spectra at selected locations in the reactor. All spectra normalized to

$$\int_{u=0}^{\infty} \varphi(u)\, du = \int_{E=14.9\,\text{MeV}}^{0} \varphi(E)\, dE = 1.$$

Fission energy. - For this core the median fission energy was calculated to be 0.36 MeV.

THERMAL AND FLUID FLOW DESIGN

Calculation Procedures

The temperatures and flow distribution within the reactor core were determined using a modified version of the computer program MCAP (ref. 8). This program was originally written to handle flow and temperature distributions within a gas-cooled reactor. The program has been revised, however, to handle incompressible as well as compressible flow problems. It is therefore suitable for the analysis of a liquid-metal-cooled reactor.

In this program (MCAP), reactor coolant passages with similar nuclear and geometric characteristics are grouped together. The flow and temperature distributions in this parallel channel geometry are determined by balancing the pressure loss across the core so that the pressure drop in each channel is the same.

In the zoned core, approximately nine flow channels are required to simulate the various fuel zones and local power variations in the reactor. An additional flow zone is required to simulate the passive flow in the tricuspid area between the honeycomb tubes (fig. 2). Also, another flow zone is used for the region between the core and the pressure vessel (fig. 3). The computer code varies the flow to each of these flow zones until the various combinations of flow rate and power input results in a uniform pressure loss across each channel.

Fuel temperature calculations were based on standard one-dimensional heat-transfer relations for conduction and convection in conjunction with the following correlation developed in reference 9 for annular flow of liquid metals:

$$\mathrm{Nu} = \alpha + \beta (\overline{\psi}\,\mathrm{Pe})^{\gamma}$$

where

Nu Nusselt number

α 4.82 + 0.697 y

y ratio of outside to inside annuli

β 0.0222

$\overline{\psi}$ $1 - \dfrac{1.82}{Pr\left(\dfrac{\epsilon}{v}\right)_{max}^{1.4}}$

Pe Peclet number

γ $0.758\ y^{0.053}$

Pr Prandtl number

ϵ eddy diffusivity

v kinematic viscosity

Core Temperature and Flow Distribution

As noted in the previous section the flow and temperature distribution within the liquid-metal-cooled core are determined by balancing the flow in each channel to obtain a uniform pressure drop across the core. Since the nominal coolant temperature rise in the core discussed here is only 55 K (100° R) from the 1167 K (2100° R) inlet to the 1222 K (2200° R) outlet, there is very little maldistribution of flow caused by temperature variation across the core. Also, the coolant density and viscosity variations are relatively small (ref. 10). The density varies by 1.25 percent, and the viscosity by 6.9 percent for this temperature variation. The total maldistribution of flow is less than 1 percent assuming that the flow distribution in the inlet plenum is sufficiently uniform to assure proper distribution to the various channels.

By orificing the passive flow area and the flow area between the core and pressure vessel, the flow to each can be held to 6 percent of the total. This means that 88 percent of the coolant passes through the active core and is used to directly cool the fuel elements. The overall pressure loss for the core is only 0.51 newtons per square centimeter (0.74 psi). The flow characteristics are summarized in table VII.

With a nominal coolant temperature rise of 55 K (100° R) across the core and with the assumption that the power transferred to the passive flow areas is small, the average coolant temperature rise in the fuel element coolant passages is about 63 K (114° R). The channel with the maximum radial power factor has an additional 20 percent (including 5 percent to account for the average power factor increase between beginning and end of life conditions) in coolant temperature rise, so that the maximum lithium-7 temperature rise (neglecting possible hot channel factors) is 76 K (137° R). The radial distribution of exit coolant temperatures is shown on figure 8 and follows the radial power distribution in figure 9 closely.

The radial variation of maximum fuel temperature (also shown on fig. 8) does not,

TABLE VII. - FLOW CHARACTERISTICS

[Total coolant flow, 9.39 kg/sec.]

Flow area	Fraction of total flow, percent	Reynolds number	Coolant velocity		Radial variation, percent
			m/sec	ft/sec	
Active core	88	4850	1.16	3.8	1.0
Passive	6	650	.15	.5	---
Peripheral	6	3800	.09	.3	---

	Core pressure drop	
	N/cm^2	psi
Inlet	0.152	0.22
Friction	.214	.31
Outlet	.145	.21
	.511	.74

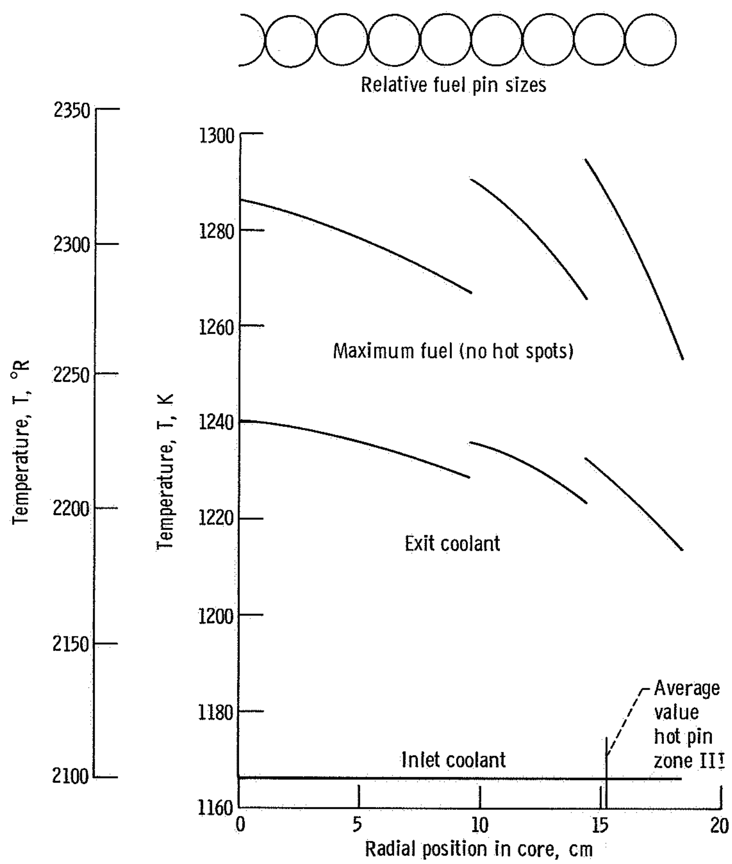

Figure 8. - Temperature distribution in zoned core.

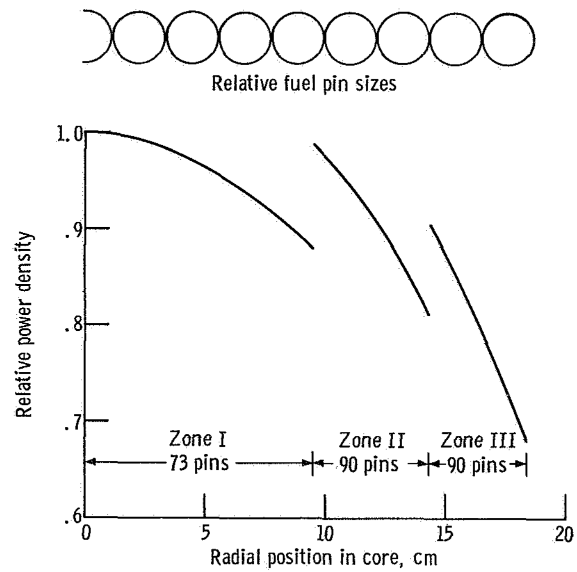

Figure 9. - Radial power distribution, zoned core.

however, follow the radial power distribution. In fact, the maximum fuel temperature of 1289 K (2320° R) occurs in zone III at a point where the radial power density is nearly 10 percent lower than at the core center; this is because the fuel is thicker in zone III than in either of the other zones (table VIII). The nearly 50 percent thicker fuel, even though combined with a 10 percent lower power factor, results in the higher temperature.

This fact warns against trying to flatten the radial power distributions too much since both fuel swelling and creep strength of the cladding are temperature dependent. Additional fuel in zone III would result in a temperature increase in the fuel, increased fuel swelling, and the probability of exceeding the clad creep limit. The present design would result in not more than 1 percent creep in the fuel-element cladding. Reference 1 discusses a similar situation of creep limited reactors in which completely uniform power distributions are not desirable.

The axial temperature distribution in the channel with the maximum fuel temperature is shown in figure 10. The temperatures shown are based on the average radial power for that channel (fig. 9) and assume intimate contact between fuel and clad. If

TABLE VIII. - FUEL DIMENSIONS

	Fuel zone		
	I	II	III
Number of pins	73	90	90
Thickness of annular fuel region, cm (in.)	0.367 (0.1445)	0.442 (0.174)	0.536 (0.211)
Diameter of central void, cm (in.)	0.851 (0.335)	0.701 (0.276)	0.513 (0.202)

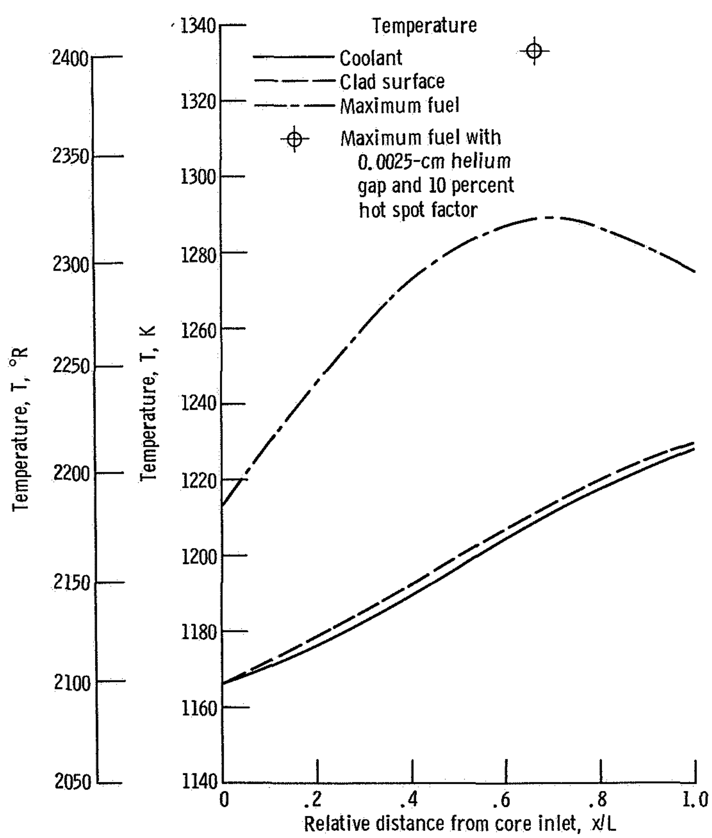

Figure 10. - Axial temperature variation (average value), zone III fuel pin.

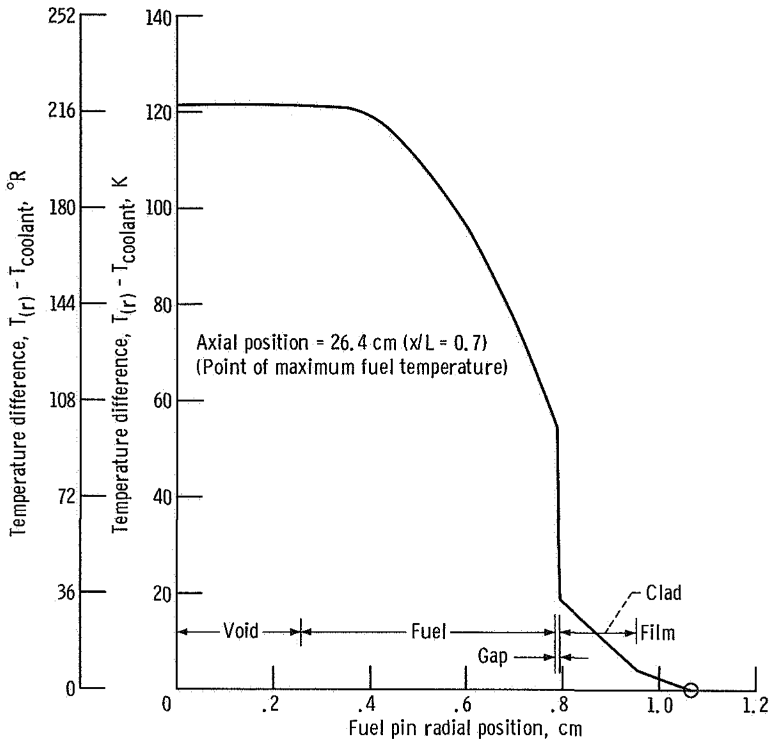

Figure 11. - Hot spot temperature distribution through cross section of zone III fuel pin (includes 10 percent hot spot factor plus 0.0025-cm helium gap).

intimate contact is not achieved, the temperatures would be higher. For example, with a 0.0025-centimeter helium gap between fuel and clad and a possible 10 percent hot spot factor, the maximum fuel temperature would be 1333 K (2400° R) as shown in figure 10. The radial temperature profile for this fuel pin is shown in figure 11.

Blockage of Flow Channel

If one flow channel became blocked as a result of corrosion plugging or a similar malfunction, the heat from that fuel pin would be conducted across the passive flow area and be dissipated in the coolant of the adjacent six fuel pins (fig. 2). The increase in the maximum temperature of the fuel (even assuming flow blockage of the hottest fuel pin) is only 44.5 K (80° R).

Reflector Temperature Distribution

Cooling of the annular radial reflector sections is a special problem because of their location and because of the mass of metal involved. Since the annular sections slide axially from the reactor midplane towards the ends of the core for reactivity control, convective cooling is impractical because it is necessary to have essentially a void region surrounding the pressure vessel to shut the reactor down. Fortunately, however, the thermal conductivity of the reflectors is good and the heat generation rate is low (table IX and fig. 12). These facts make it possible to cool the reflectors radiatively.

Calculations have been made assuming that the outermost stationary reflector is

TABLE IX. - HEATING RATES IN REFLECTOR REGION[a]

Component	Material	Radial position		Heating rate		
		cm	in.	Gamma, W/cm^3	Neutron, W/cm^3	Total, W/cm^3
Pressure vessel	T-111	19.43 20.06	7.65 7.90	1.003 .869	------ ------	1.003 .869
Inner reflector	Molybdenum	20.21 24.20	7.96 9.53	0.377 .278	0.016 .0108	0.393 .2888
Middle reflector	Molybdenum	24.43 28.88	9.62 11.37	0.277 .168	0.0108 .0051	0.2878 .1731
Fixed reflector	Molybdenum	29.03 31.57	11.43 12.43	0.168 .102	0.0051 .0016	0.1731 .1036

[a]End points from unpublished data by Gerald P. Lahti. Linear interpolation for intermediate points.

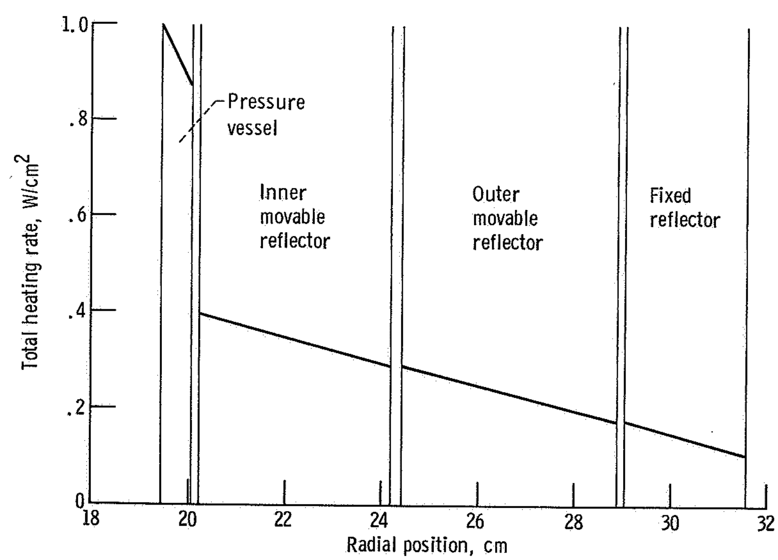

Figure 12. - Radial distribution of heating rate in radial reflector.

cooled convectively to 833 K (1500° R) and that the inner surface of the pressure vessel is maintained at 1222 K (2200° R) by the reactor coolant. Heat transfer between the movable annular reflector regions takes place by radiation only. Emissivities used are those for the smooth metal surfaces. The pressure vessel is constructed of the tantalum alloy T-111 with an emissivity of 0.150. The reflectors are molybdenum with the emissivity varying from 0.05 to 0.12 depending on temperature.

The results, shown by the bare-surface curve of figure 13, indicate very small temperature differences across the thickness of the annular reflector sections because of the high thermal conductivities. The movable regions have temperatures somewhat higher than the pressure vessel.

The other curves on figure 13 show the effect of increasing surface emissivites. An increase to a value of about 0.3 reduces the maximum temperature in the movable reflector to the temperature of the pressure vessel. On the basis of data in reference 11, it seems reasonable to expect that coatings for the reflector surfaces may be found which have emissivities of about 0.3.

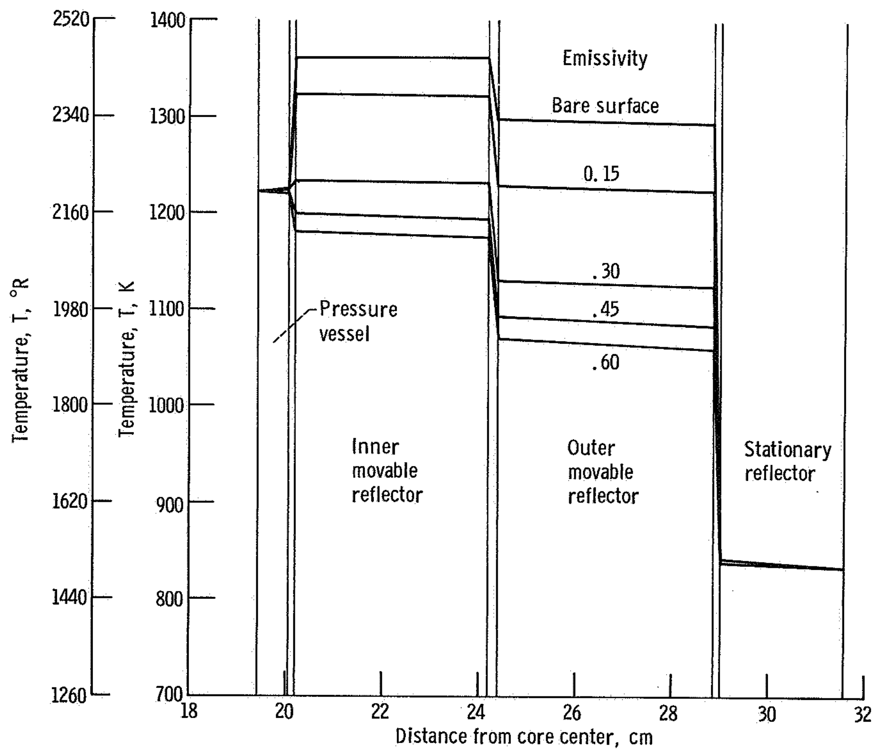

Figure 13. - Radial temperature distribution in reflectors.

SUMMARY OF RESULTS

Neutronic, fluid flow, and heat-transfer calculations were performed on a reactor concept designed to produce 2.17 thermal megawatts for 50 000 hours with a coolant outlet temperature of 1222 K (2200° R). The core had an average fuel loading of 38.0 volume percent uranium nitride enriched to 93.2 percent uranium-235. To equalize cladding stresses during core life, the fuel was arranged in three radial zones having 33.4, 37.7, and 42.0 volume percent uranium nitride, respectively. Pertinent design data calculated for this core are as follows:

Fuel pins enriched to 93.2 percent uranium-235; lithium-7 coolant; core life, 50 000 hours; control system, axially moving radial reflectors; core size, 37.6 centimeters long by 36.1 centimeters equivalent diameter

Neutronic	
Cold-clean multiplication factors	
All reflectors inserted (1.055 required)	1.0925
Movable reflectors withdrawn (shutdown, 0.964 required)	0.9905
Average core flux, neutrons/(cm^2)(sec)	1.03×10^{14}
Peak core flux, neutrons/(cm^2)(sec)	1.6×10^{14}
Median flux energy, MeV	0.48
Peak to average power	
Reflectors inserted	1.36
Movable reflectors withdrawn	1.57
Reflector control worth, % $\Delta k/k$ (9.2 required)	9.4
Fuel destroyed (average), % uranium-235	3.30
Thermal hydraulic	
Coolant temperature, K ($^{\circ}$R)	
Core inlet	1167 (2100)
Core outlet	1222 (2200)
Coolant pressure drop, N/cm^2 (psi)	0.51 (0.74)
Maximum fuel temperature, K ($^{\circ}$R)	1289 (2320)
Coolant flow, kg/sec	
Active (along fuel pins)	8.26
Passive	0.56
Peripheral	0.56

Additional results from the design calculations are listed as follows:

1. A design change required to preclude a water immersion accident would decrease the reflector control swing to 7.9 percent $\Delta k/k$.

2. The temperature defect (excluding the Dopper effect) from cold critical (460 K) to full power operation is 0.90 percent $\Delta k/k$.

3. The axial fuel expansion coefficient is 1.02 percent $\Delta k/k$ per centimeter.

4. Total loss of lithium-7 coolant from the core reduces reactivity by 0.5 percent $\Delta k/k$.

5. Substitution of molybdenum and of tungsten - 30 percent molybdenum - 25 percent rhenium as fuel cladding material increases core reactivity by 6.0 and 2.7 percent $\Delta k/k$, respectively.

6. Substitution of natural lithium as reactor coolant reduces core reactivity by 1.9 percent $\Delta k/k$.

7. Significant changes in composition of the axial plenum and reflector caused little effect (<0.1 percent $\Delta k/k$) on core reactivity.

8. With pressure drop balanced across all active flow channels, a radial flow variation of less than 1 percent exists across the core.

9. The maximum fuel temperature of 1289 K (2320° R) (and maximum cladding stress) occurs in the peripheral fuel zone.

10. If a 0.0025-centimeter (1-mil) helium gap exists between the fuel and cladding (instead of an intimate bond) and if a 10-percent hot spot factor is assumed, maximum fuel temperature will be 1333 K (2400° R).

11. Blockage of one flow channel would increase the temperature of the adjacent fuel by 44.5 K (80° R).

12. The movable radial reflectors can be passively cooled at design power to 1364 K (2455° R) by thermal radiation from the bare metal surfaces.

13. A surface coating on the molybdenum radial reflectors to increase the emissivity to about 0.3 is required to reduce the maximum reflector temperature to the pressure vessel temperature (1222 K or 2200° R).

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 7, 1969,
120-27.

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